Use of Web Technology in Monitoring Tunnel-Induced Deformations in Railroads

Integrating simple Web-based technology with existing data acquisition and processing systems provides a low-cost instrumentation monitoring environment with rapid response time for modifications.

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The Central Artery/Tunnel (CA/T) Project is currently the largest government-funded public works project in the United States. An existing elevated highway, constructed in the 1950s, is being phased out and replaced with a tunnel alignment through downtown Boston, Massachusetts. Figure 1 shows the project location. An integral element of the project is the Ted Williams Tunnel, which crosses Boston Harbor. The highway alignment leading to the Ted Williams Tunnel includes a portion that is jacked beneath the mainline commuter railroad tracks that feed into South Station in Boston's Financial District (construction contract C09A4). This alignment crosses the existing tracks with less than 15 feet of groundcover. Therefore, a monitoring system to evaluate the settlement and heave of the tracks was required since the commuter railway had to remain in service without interruption during construction.

Background

Geological Setting. Contract C09A4 is located on filled land adjacent to the Fort Point Channel (a natural inland waterway that was reduced in size during nineteenth century land filling). An idealized subsurface geologic profile of the site consists of miscellaneous fill, soft organics, silts and sands, Boston Blue Clay, dense to very dense glacial till and argillite bedrock of variable quality.

The groundwater regime consists of two water tables: one perched in the fill, organics and sands above the marine clay deposit; and the

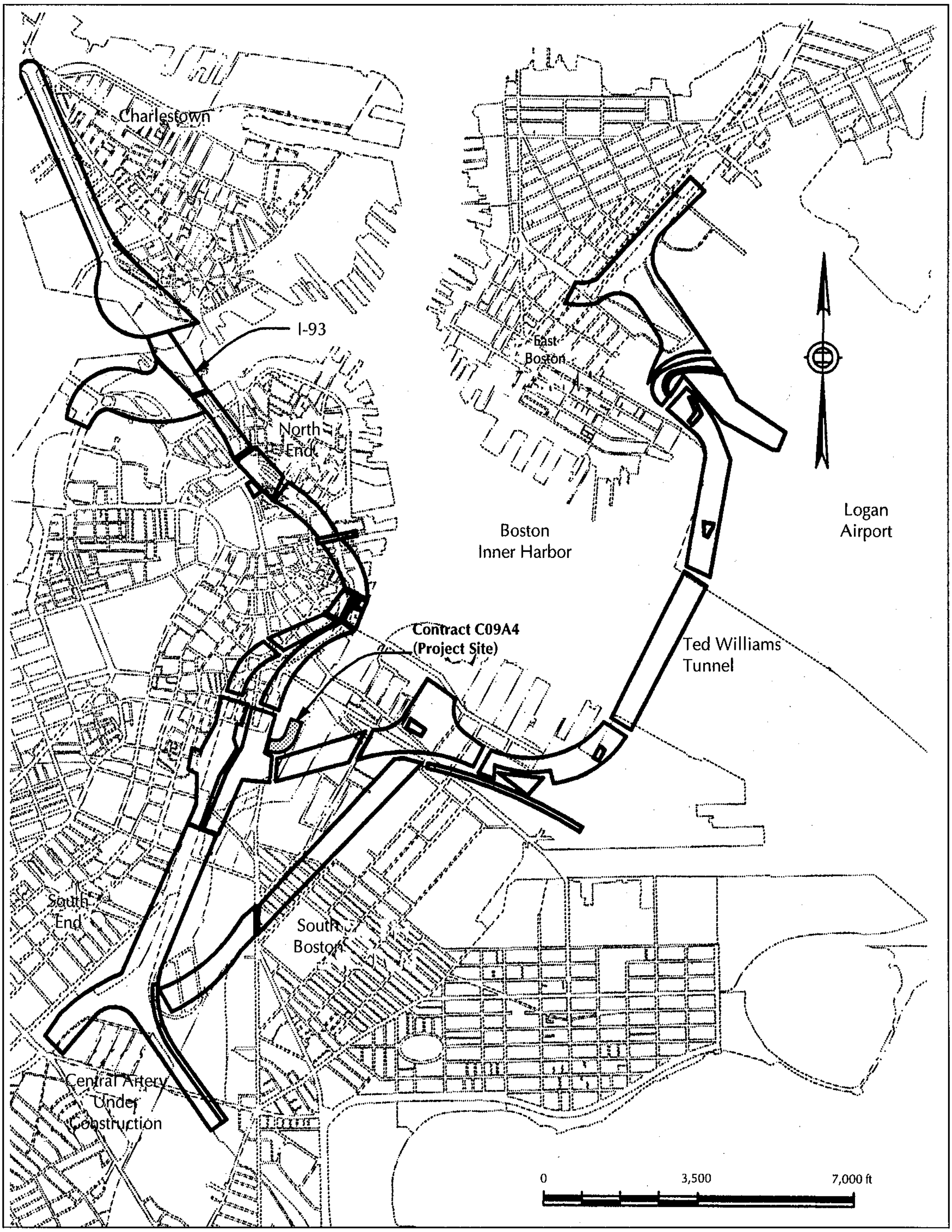

FIGURE 1. Location plan.

other a lower confined aquifer, located in the glacial till and bedrock. The perched aquifer phreatic surface generally varies from elevation 100 to elevation 105, with tidal fluctuations due to the close proximity of the site to Fort Point Channel. Piezometric levels measured in the deep glacial deposits and bedrock vary from elevation 93 to elevation 97.

Site Development History. The site lies within an area that was once covered by seawater, tidal marshes and shorelines. Landfilling in this area began in the early 1800s and was essentially completed by the 1840s. Much of the filling material came from gravel pits, with some fill coming from the dredging of tidal marshes. The gravel was transported by railroad to the site.

An agreement in the 1830s gave the Boston and Worcester Railroad the right to purchase the filled land in order to establish and maintain railroad facilities. The development of this area has been tied to railroads from the 1830s to the present.[1]

Wharf construction in the area took place from the early to mid-1800s as part of the filling that narrowed the Fort Point Channel waterway. There were also other commercial structures, such as a coal gasification plant. Many of the wood pile and granite block foundations were left in place and they posed potential obstructions to the jacked tunnels.

Overview of Contract C09A4. Notice to proceed was issued to the contractor in June 1997 for a contract duration of four years. The main element of the contract is the jacking of the I-90 tunnels beneath the commuter rails serving the South Station Terminal. The jacked tunnels are approximately 30 to 35 feet tall and 45 to 80 feet wide. Shield tunneling methods will be used to jack the tunnels. The contractor has adopted ground freezing as the main element of ground movement control during tunnel jacking. The Massachusetts Bay Transportation Authority (MBTA), as the owner of the tracks, imposed the allowable track movement values based on the Federal Railroad Administration's (FRA) criteria. Settlement or heave of the tracks beyond the allowable limits trigger actions such as the reballasting of the tracks or additional grouting at the tunnel face. The FRA criteria assess settlement, twist, warp, spiral and low point of the tracks.

Instrumentation Program

The railroad tracks are monitored primarily by using deformation monitoring points (DMPs) and optical monitoring methods. Two types of DMPs are being used on the rails. The first, a Type 6 DMP (DMP6), is a point on the top of each rail and is identified by a paint mark (see Figure 2). The DMP6s monitor the elevation of the rails in the absence of trains and provide the *static rail elevation.* Since the tracks have the ability to span cavities and depressions in the subgrade due to their rigidity, the monitoring of the DMP6s by themselves may not give an accurate picture of the track when it undergoes heavy loading due to the passage of a train. Therefore, a second type of DMP, a Type 8 DMP (DMP8), is used to measure the elevation of the tracks under this loaded condition. This instrument is a 15-inch steel rod that is driven into the subgrade beneath the rail (see Figure 3). As the train passes, the rod is pushed into the subgrade, where its elevation is subsequently recorded and provides the *dynamic rail elevation.* The FRA criteria are applied to both rail conditions.

These DMPs have been augmented with borros anchors and probe extensometers for monitoring the settlement of the ground below the subgrade of the tracks, as well as with inclinometers to monitor horizontal ground movement in front of and on the sides of the tunnel shield.

Data Management System

Overview. The cornerstone of the monitoring system is a requirement by the MBTA to take readings of the track elevations three times daily during tunnel jacking operations, and to be able to evaluate the results within one hour of each survey. The system was developed to perform all calculations of the FRA track criteria on the readings collected and publish the results on a web page, which is concurrently accessible to the railroad authorities, the construction contractor and CA/T Project management consultant personnel.

The reduced data are also integrated with a GIS application that the management consultant maintains projectwide.[2] The GIS application allows a variety of reports and plots to be prepared in a short time frame. The web page is used to give the user a quick, accurate and detailed picture of the latest readings and potential trouble spots. The GIS application gives the user the capability of plotting profiles of rail

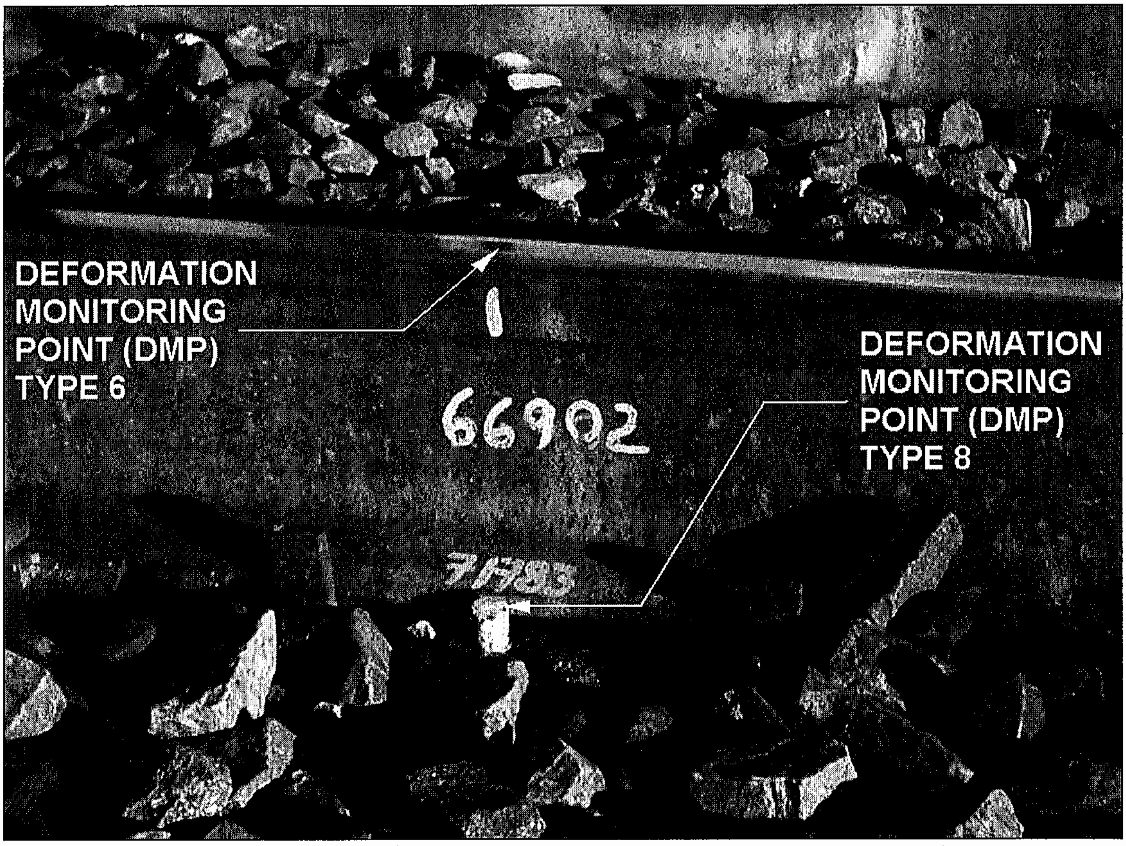

FIGURE 2. Typical DMP Types 6 and 8 paired installation spaced at 15.5-foot (1/4-chord) intervals.

routes and settlement/heave contour plans to assess changes in elevations on a large or small scale, as well as plots that give a time history of specific settlement points for a more in-depth analysis.

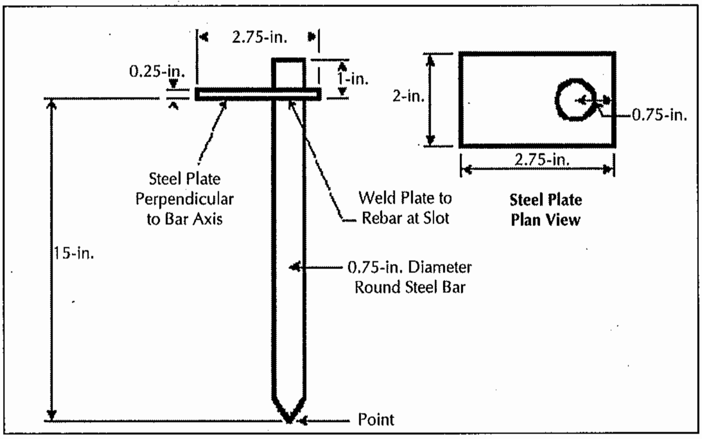

FIGURE 3. DMP Type 8 detail.

Data Collection. The system performs all calculations of the track criteria based on elevations obtained from either the DMP 6s or DMP8s. Elevation observations of the DMPs are obtained with digital levels and sectionalized bar coded level rods. The digital level observes the bar-coded rod to sub-millimeter (mm) precision, and has a standard accuracy of ±1.5 mm (0.06 inches) for one kilometer of double-run leveling. The digital level uses a charged couple device (CCD) similar to that found in video cameras. The CCD sensor captures an image of the divisions on the bar-coded rod. An internal correlation process calculates a rod reading and a distance-to-rod value from the analog video signal.[3] These results are then stored in an on-board stor-

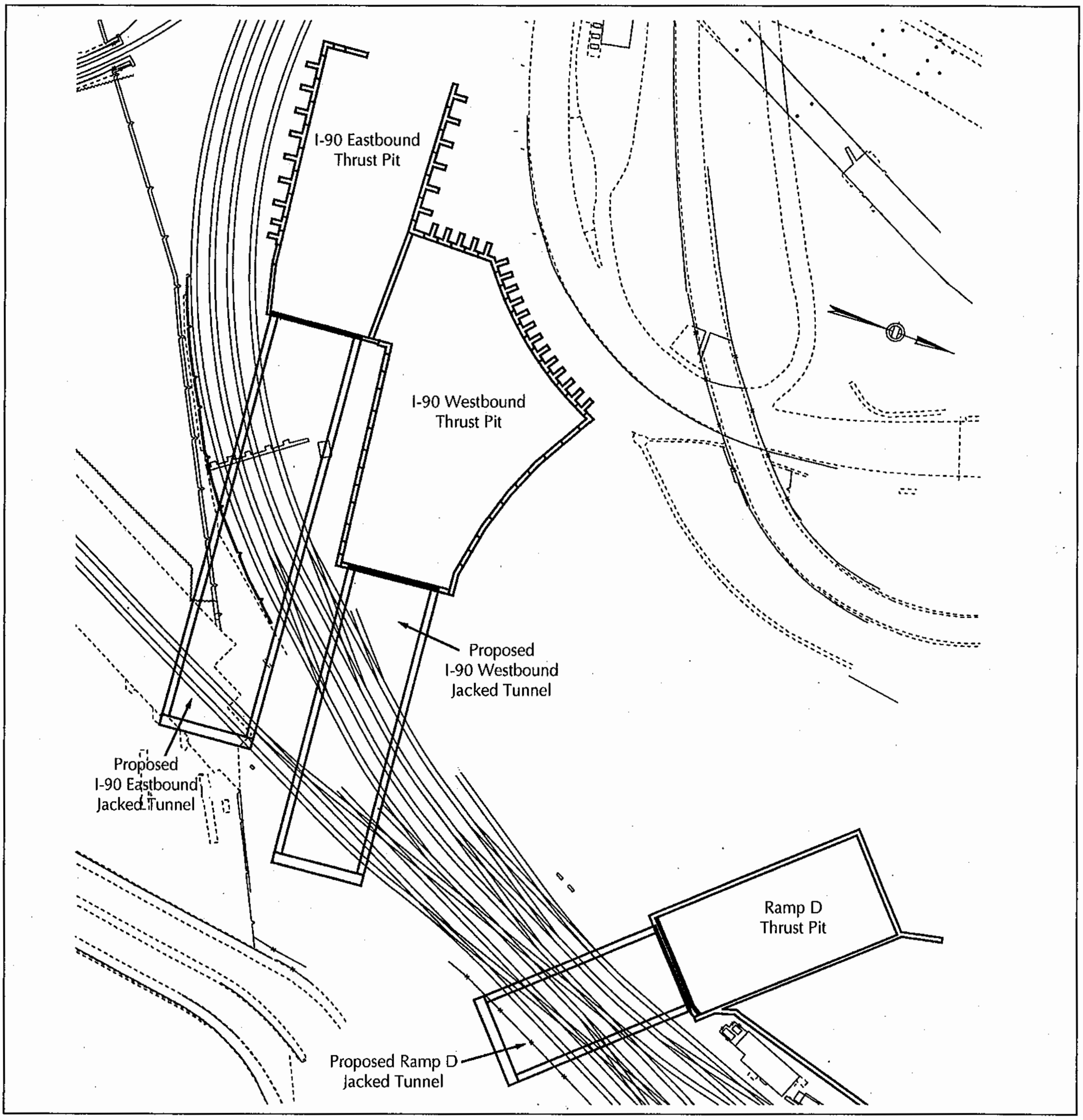

FIGURE 4. Location of Ramp D thrust pit.

age device along with the point number identification, pre-set standard error of the readings, and numeric observation and message codes. Each set of observations begins and ends on a deep benchmark that is part of the CA/T Project vertical control network.

The raw, unadjusted field observations are downloaded to a personal computer (PC) where the data are run through proprietary preprocessing software to aid in detecting and removing errors, and to format the file for adjustment of the level run. To ensure consistency in monitoring results, the data are adjusted by passing them through a least squares adjustment program. The resulting elevations and DMP identifications are formatted in a spreadsheet for batch loading into the system. This computational procedure allows for a seamless digital (versus manual) processing of the data to the point of system uploading. During the batch loading process, a survey upload report is generated that identifies any errors encountered in the survey data. A typical error encountered could be "DMP ID NOT FOUND,"

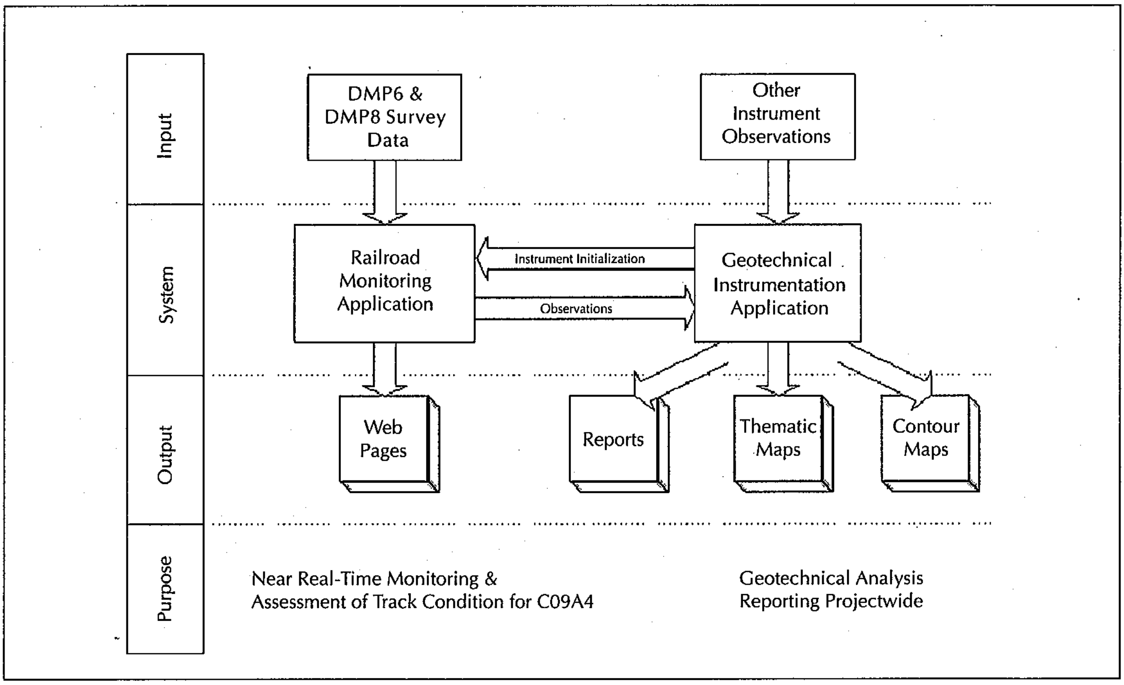

FIGURE 5. Diagram of the railroad monitoring system components.

which would have resulted from an erroneous DMP identification entered during an observation. At this point the data have not yet been entered into the system and two upload options exist. The first is to accept the data set and allow the acceptable data to be uploaded. The surveyor can then resolve any errors such as those caused by transposed DMP identification numbers, and re-upload the remaining data. The second option would be to cancel the upload process, reprocess the data to resolve the errors and then re-upload the data set to the system.

Current Construction Status. The C09A4 contractor is currently constructing the jacking thrust pits that are located within 10 feet of the tracks. The Ramp D thrust pit (see Figure 4) has been excavated to the base slab elevation of 50 feet (which is 65 feet below the tracks). The tracks at Ramp D have been monitored twice per week during slurry wall installation and pit excavation.

As of June 2000, over 3,000 instruments (DMP6s and DMP8s) have been installed throughout the contract area. With the completion of the Ramp D tunnel and the jacking of the I-90 Eastbound and Westbound tunnels, monitoring is occurring twice daily, seven days a week. Many instruments within the areas of active tunneling are being observed two times per day. At this stage in construction, the database contains over 399,000 observations.

Database Structure/Data Entry & Reduction. The system was designed to meet these objectives:

- to support a high volume of observations;
- to make calculations available within one hour of the completion of the survey;
- to facilitate access to FRA calculation results;
- to minimize requirements on systems to enable support of both wide area networks (WANs) and dial-in users; and,
- to allow a variety of users with differing computer and computational expertise to easily view the results of the track surveys;

Placing the data on a web site was selected as the architecture best suited to quickly deliver a high volume of FRA calculations to users with minimal additional hardware requirements and minimal additional software investment and training. Because of the sensitive nature of the data made available to users, the system is deployed as an Intranet, in which only autho-

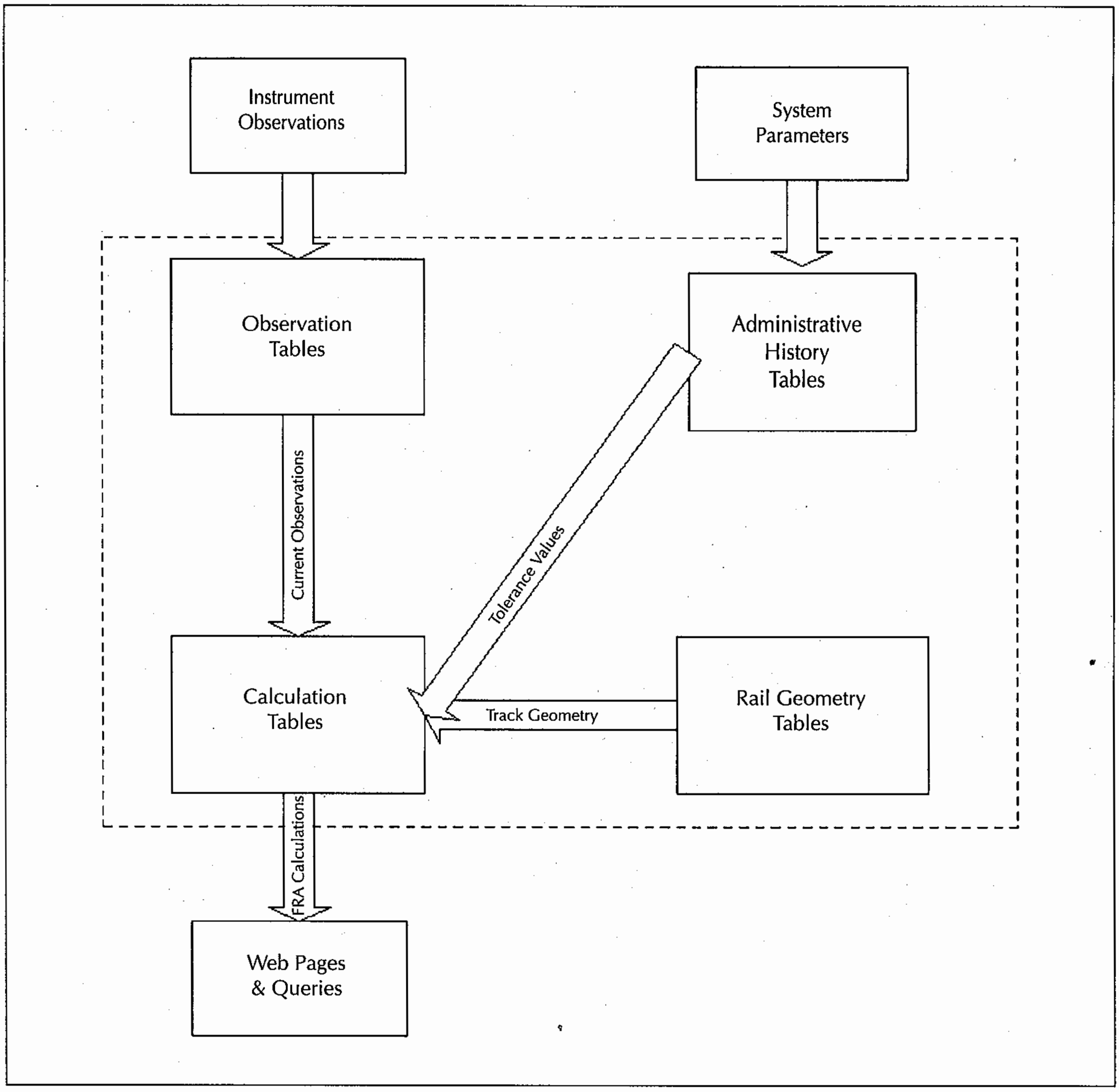

FIGURE 6. The structure of the railroad monitoring database.

rized users have access via the CA/T Project WAN or dial up services. Web technology also provides benefits in ease of use, because all operations are performed by "point-and-click" operation. Additionally, users can obtain more detail about specific locations and instruments by clicking on hyperlinks, thus enabling efficient navigation through large volumes of data.

Figure 5 illustrates the system used to manage and process the data. The CA/T Project instrumentation database contains the locations and characteristics of the DMP8 and DMP6 instruments used for monitoring. A separate database (on a different server) is used to store the observations for railroad monitoring. A dedicated database permits improved fine tuning for the greater frequency and volume of observations, and provides a platform for various programs to perform calculations and publish the results (such as one to contour changes in rail elevation).

The programs that perform calculations and publish results run continuously on the railroad monitoring server. These programs publish results in static hypertext mark-up language (HTML) pages (for summaries) and by dynamically generated HTML pages (for detailed reports). Calculation and publishing

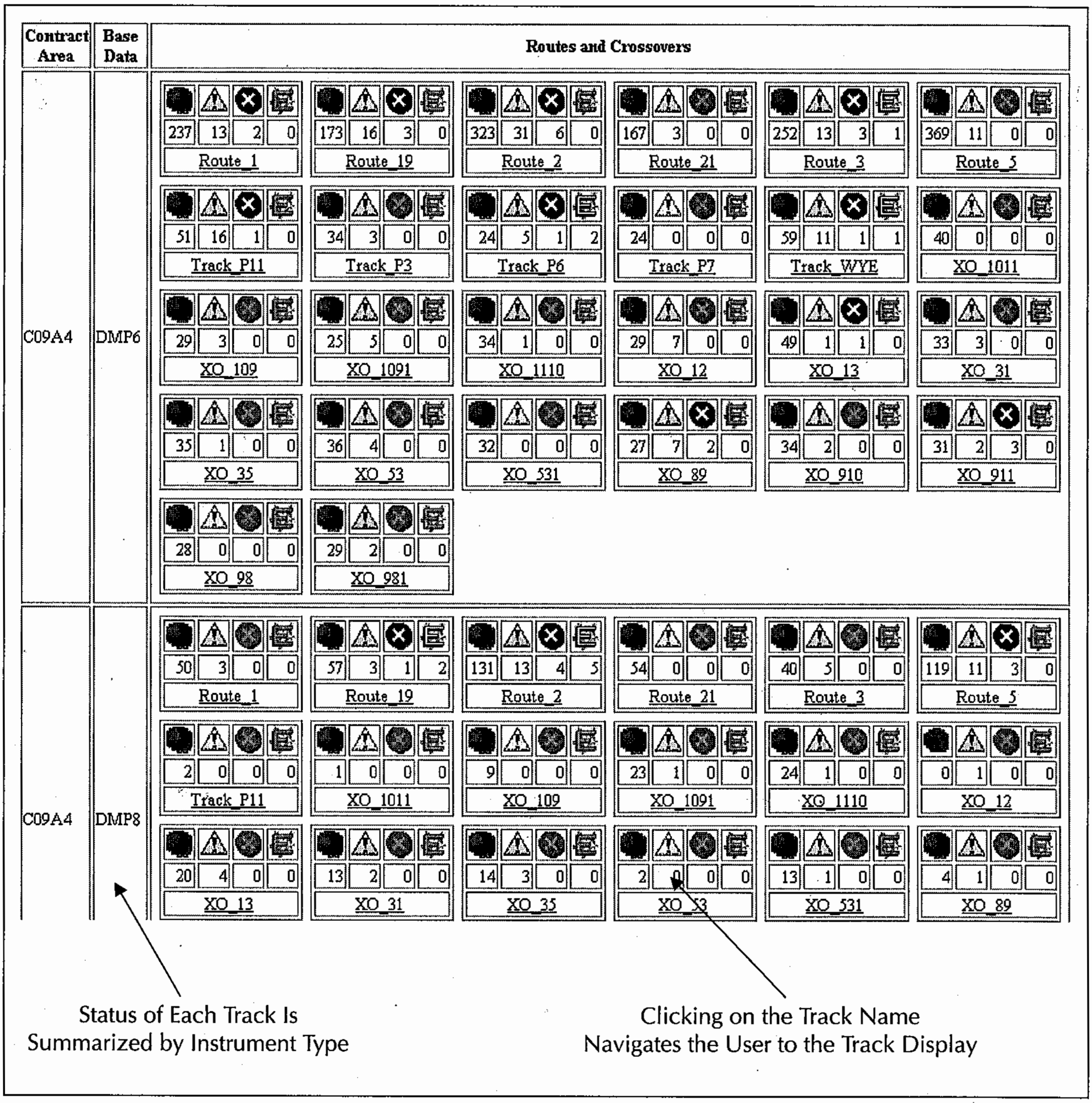

FIGURE 7. An example of the main web page of track summaries.

tasks are performed automatically, immediately after observations have been uploaded to the system. Users gain access to the information using standard web browsers via the CA/T Project WAN, or by dialing in with modems to the railroad monitoring server. Calculations are typically visible on the web site within 60 minutes after observations are received from field crews. As new calculations are available, they are made immediately visible to users.

The database used to manage the railroad monitoring data is structured into four areas (see Figure 6 on the previous page):

- Observations are stored when survey analysts perform the uploading process, which is the last step of the data collection process.
- Geometry information stores the relationship of instruments to the track stations, and the geometry of the track at each station.
- Calculations are stored by the program that computes the FRA metrics for each track station.
- Administrative information is used to control the calculation and publishing

Calculation Result Is in Yellow (Warning) State

Distance Station	Instr. Station	Note	Geo-metry	North Profile Deviation	South Profile Deviation	Elevation Deviation Spiral	Variation (Warp) in Spiral	Cross Level	Warp
316+34.2	142		T	0.17	0.11			0.42	0.40
316+49.7	143		T	0.48	0.46			0.44	0.25
316+65.	144		T	0.54	0.54			0.67	0.50
316+80.6	145	I90 WB S.EDGE	T	-0.43	-0.46			0.47	0.48
316+96.1	146		T	-1.05	-0.67			0.92	0.52
317+11.6	147		T	0.05	0.28			0.56	0.72
317+27.2	148		T	0.77	0.61			0.41	0.72
317+42.6	149	I90 WB CL	T	0.85	0.71			0.20	0.44
317+58.	150		T	1.01	0.83			0.22	0.29
317+73.5	151		C	0.39	0.37			0.12	0.29
317+89.1	152	I90 WB N.EDGE	C	0.29	-0.01			0.37	0.41
318+04.6	153		C	0.07	0.05			0.08	0.41
318+20.3	154		C	0.55	0.20			0.04	0.41
318+35.8	155		C	0.07	0.06			0.08	0.29
318+51.4	156		T	0.02	0.33			0.25	0.34

Calculations Based on Observations Less Than 24 Hours Old

Calculations Based on Observations More Than 48 Hours Old

Calculations that are older than the data currency threshold (14 days as of 6/2/98) are displayed with a grey tint. The following table illustrates possible states and positions.

Metric	Value	Description
Profile	-0.55	This value is within the upper limit of the *green* state and is less than 24 hours old.
Spiral	1.00	Not greater than upper *green* limit of 1", but is based on data more than 48 hours old.
Variation in Spiral	1.24	Within *yellow* state for spiral variation calculation, from 24 to 48 hours old.
Cross Level	1.27	*Red* state, less than 24 hours old.
Warp	1.60	This metric is in the *emergency* state and is based on observations taken within the past 24 hours.

FIGURE 8. An example of the web page for a track.

process, and maintains a history of the changes to the database.

Each uploading session of observations to the database automatically triggers the initiation of calculations. FRA metrics for profile deviation (both rails), cross level deviation (for both tangent/curve and spiral rails) and warp (for both tangent/curve and spiral rails) are calculated at each station on each track. The most recent observations available are used in the calculations. A time tolerance, stored in the database, controls the maximum time difference allowed in the observations used for a calculation. Each calculation requires between two and ten observations; the date and time of the oldest observation is

Static Readings: DMP6											
Distance Station	**Instr. Station**	**Note**	**Curve Data**	**Rail**	**DMP**		**Status**	**Date**	**Elevation**	**Change**	**Total Change**
316+96.1	146		T 0	Left	66248	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.17' 117.09'	-1.04"	-1.04"
				Right	66969	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.24' 117.16'	-0.95"	-0.95"
Chord Readings: DMP6											
316+65.	144		T 0	Left	66247	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.13' 117.03'	-1.24"	
				Right	66968	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.17' 117.08'	-0.99"	
316+80.6	145	I90 WB S.EDGE	T 0	Left	43881	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.16' 117.07'	-1.16"	
				Right	43882	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.20' 117.11'	-1.07"	
316+96.1	146		T 0	Left	66248	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.17' 117.09'	-1.04"	
				Right	66969	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.24' 117.16'	-0.95"	
317+11.6	147		T 0	Left	66251	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.28' 117.23'	-0.60"	
				Right	66970	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.32' 117.28'	-0.46"	
317+27.2	148		T 0	Left	66254	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.37' 117.32'	-0.56"	
				Right	69680	FIR Obs.	ACTIVE ACTIVE	18-May-1998 08:43 16-Dec-1998 12:00	117.39' 117.35'	-0.44"	

Calculated values for Route_3 instrument station 146.

Metric	**Base Date**	**Value**	**Upper Limit**			
			Green	**Yellow**	**Red**	
Left Profile	16-Dec-1998 12:00:00	-1.05	2.00"	2.25"	2.75"	
Right Profile	16-Dec-1998 12:00:00	-0.67	2.00"	2.25"	2.75"	
Spiral			1.00"	1.25"	1.50"	
Variation in Spiral			1.00"	1.25"	1.75"	
Cross Level	16-Dec-1998 12:00:00	0.92	0.75"	1.25"	1.50"	
Warp	16-Dec-1998 12:00:00	0.52	0.75"	1.25"	1.50"	

FIGURE 9. An example of web page output for a single instrument station.

stored as the date and time of the calculation. After the calculation is performed, the system applies criteria to the calculation to determine its status as compared to the FRA criteria. The status is indicated by the use of symbols and colors — green (normal), yellow, red, and emergency (red capital 'E'). The criteria are stored in the database, enabling the system administrators to modify them if requested.

A main page enables users to select an instrument type (static DMP6 or dynamic DMP8) and a track to view the status of the FRA calculations (see Figure 7 on page 46). The first page for each track (a summary) shows the status of calculations at each instrument station (see Figure 8 on page 47). Visual queues are provided that indicate the status of each calculation (indicated by the color and shape of the symbol) and the age of the observations used (indicated by the horizontal location of the symbol). This summary page provides the means for a rapid review of the status of a track and of any conditions that require attention. The pages reload automatically after an interval defined in the database (typically, 5 minutes), which provides the latest calculations without the user having to initiate intervention. Detailed results at each station (see Figure 9) are available by clicking on the particular instrument station. Clicking on a station hyperlink is the equivalent of performing a query for more detailed information about the calculations and observations at that station. The results are generated dynamically using a custom module integrated with the web server. The query results include the observations in the 62-foot chord used to generate the calculation. Additional information is obtained by clicking on an instrument hyperlink. This query provides details of all previous observations from the selected instrument.

The web interface enables users to select tracks with a simple click and then review particular instrument stations where problems may exist, review the observations that calculations are based on and review the history of observations for a particular instrument. This setup provides users with much easier and faster access to data than would be possible using hard copy reports. The benefit to the project is that users can quickly and accurately make better-informed decisions based on current track conditions.

Further analyses of the data are performed by preparing tabular hard copy reports, and plans and plots. Settlement contour plans and profiles are available through the projectwide GIS application. Most parameters — such as spacing, scale, DMP type and colors — can be specified by the user. Plots of settlement versus time are generated using the database, and are accessed in a plotting program.

Conclusions

Publishing the FRA based track conditions on a web site that is accessible to all pertinent parties allows them to quickly assess any impact due to construction. In the Ramp D area, with multiple cross-overs and double-slip switches, it is imperative to quickly determine potential problems so that track inspection personnel can immediately focus on them. This ability to view track conditions speeds response time in modifying the frequency and/or area of track to be monitored to ensure that field inspection resources are covering to the area(s) of greatest interest.

Furthermore, the web page provides a common basis for track condition assessment and decision making. Web technology has made the system accessible to a variety of users, both within the CA/T Project and in partner organizations, because the client system requirements (web browser and modem) are minimal.

Web technology is increasingly being applied to engineering projects throughout the world. Web technology is being used in this instance to evaluate monitoring information and make it concurrently available to a range of users in a timely manner. Although the CA/T Project is relatively large, the increasing availability and decreasing costs associated with the use of the Internet-based solutions and its software environment make it a viable solution on medium and small projects as well.

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NOTES — *All elevations refer to the Central Artery/Tunnel Project Datum, which is 100 feet below the National Geodetic Vertical Datum (mean sea level). The GIS application used was Oracle/GDS; Turbo Net was the least squares adjustment program; and EasyPlot was the plotting program.*

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REFERENCES

1. Ty, R.K.S., "History and Characteristics of Man-Made Fill in Boston and Cambridge," M.Sc. thesis, Massachusetts Institute of Technology, 1987.

2. Vaghar, S., Bobrow, D.J., & Marcotte, T.A., "Instrumentation for Monitoring Ground Movements: Central Artery/Tunnel Project, Boston, Massachusetts," Rapid Excavation and Tunneling Conference, Las Vegas, Nevada, 1997.

3. Ingensano, H., "Technical Paper Digital Levels," Leica AG, 1993.